

# Calibration of Feedback for Electromagnet Current Control

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**Abstract**— Electromagnets are used for generating magnetic field. Choi and his foes showed that magnetic field generated by electromagnets can be used for actuating microrobots [1]. Robotic systems working contactless are foreseen to be used in medical operation applications in the future [2]. The usage of Helmholtz electromagnet couples is one of the most common methods for the control of the robot, because homogeneity of the magnetic field may play a vital role for the applications where accurate controlling is required. Because of having a nonlinear system characteristic due to semiconductors in the driver circuit and the electromagnets, a correlation between the current and feedback voltage from sensing circuit is proposed with Lagrange and rational interpolation methods. In this paper, the calibration of the electromagnet drivers is handled. The measurement samples and the sampled data evaluation processes are examined. A proper form for a control system with calibrated driver is given as a resultant.

**Keywords**— *electromagnetic actuator; current feedback, microrobot*

## I. INTRODUCTION

Electromagnets are extensively used in the daily life with various of applications like transformers, electric motors, MRI devices and many of others. These systems are also prone to contactless power transmission; thus, it is seen that microrobot manipulation is also possible in medical operations [3]. The works focus on increasing the degree-of-freedom (DOF) in a controllable way as in [4] and the workspace dimensions. Thus, having an accurately controllable system is important.

An electromagnet shows magnetic characteristic only when some current flows through its coil, meaning that the magnetic field strength is not directly related with the voltage applied to the terminals of the coil. With the popular driver products available in market, current driver design is based on the driving methodology where an adjustable the voltage control is accomplished with the feedback of a current sensor [5].

Voltage driver system has a fundamental structure based on semiconductors. MOSFETs are one of the most common semiconductors in power electronics because of low cost and

high capacities. Depending on the purpose of the driver, the arrangement of circuitry may vary. Generally, to adjust the output, the semiconductors are used as switch logic which provides adjustment to the average of the output with high efficiency [6].

The current flowing through electromagnets can be measured using a shunt resistor. A basic conversion, from voltage to current, may be defined for a feedback sensor measurement.

### A. Problem Definition

Coils and driving electronics using semiconductors like IGBT and MOSFET are hard to model without uncertainties. Even if a linear model approximation is assumed, the nonlinear disturbances may cause distorted voltage drops and irregular current ripples. If the control is not achieved properly, undesired gradients of the magnetic field occur and affect the control of applied force to the object. As current plays an important role at control of magnetic field arising from an electromagnet, the calibration of the drivers is significant for the system.

There are two variables in need for correlation: Current and feedback voltage from sensing circuit. As the system transfer function and the relationship between the current feedback voltage and the current are nonlinear, with an open loop control approach, the goals are too far away from reach. First, the current feedback voltage – current relationship should be constructed. Hence, some samples from the system are required. Then, a correlation is adapted using a common method, Lagrange interpolation. Finally, a close loop control system can be built.

## II. MATERIALS AND METHODS

The structures of electromagnets used in this study is given in Figure 1. The coil of the electromagnet has a cylindrical shape and has 600 windings total, where there are 3 layers, 200 windings for each layer. The iron core has a cuboid shape for focusing the magnetic flux lines and generating greater magnetic flux intensity.

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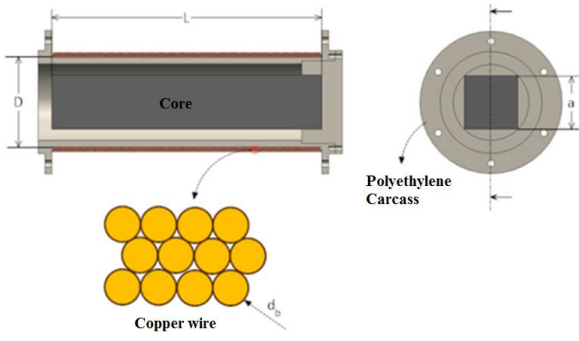


Fig. 1. Electromagnet structure.

For driving the electromagnets, PWM controlled H-bridge drivers are used. The driver card is given in Figure 2. In this system, the drivers are planned to be used in a low-frequency variation.

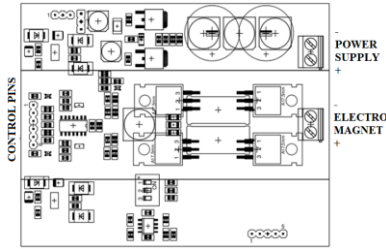


Fig. 2. Electromagnet driver card.

Coils of electromagnets are connected to the drivers as loads. The coil characteristics consist of a resistor and an inductor connected in a series way. Depending on Ampere's law, the magnetic field formulation occurring inside a cylindrical solenoid is given in (1).

$$B = \mu \frac{n}{L} I \quad (1)$$

Where  $B$  refers to magnetic field per unit length,  $\mu$  refers to permeability,  $n$  refers to number of turns,  $L$  refers to length, and  $I$  refers to current. As the environment parameters are assumed to be constant, the magnetic field strength is proportional to the current value.

#### A. Current Measurement Principle

In the sensing circuit, there exists a shunt resistor with a very low resistance value connected in a series way to the load. The voltage of this resistor is amplified by using OPAMP circuits. In the end, the voltage value can be used for current sense as a feedback. For the sample data, current is measured using a regular ampere meter. These measurements are gathered using Advantech PCI-1716 data acquisition (DAQ) card and related to Matlab Simulink for evaluation and control.

#### B. Data Processing Approach

Using these hardware and fundamental acknowledgements, the sampled input and output data are can be converged with a data processing approach. This relationship might be a

polynomial, a function, etc. form. In (2), a polynomial formed relationship is given.

$$y = a + bx + cx^2 + \dots \quad (2)$$

Here, two of the methods are given that might be used.

1) *Iteration*: Iteration can be referred as applying a repetitive process till reaching to the final value. For the intermediate values between the sample points, the iteration method might be applied. This method bears a calculation load and as the time interval for the iteration step decreases, more convenient data are resulted. One of the most common iterative method is Newton-Raphson method. The equation for this method is given in (3).

$$x_{n+1} = x_n - \frac{y_n}{y'_n} \quad (3)$$

2) *Interpolation*: In spatial plane, interpolation method is used for estimating the value with a generated curve using the sampled data. Iteration can be referred as applying a repetitive process till reaching to the final value. For the intermediate values

a) *Newton interpolation*: The fundamental of this method depends on the iterative method, Newton. According to this method, Newton divided differences, using the sampled data, the relationship as in (2) can be generated and polynomial coefficients can be determined.

b) *Lagrange interpolation*: Lagrange interpolation generates polynomial coefficients in an  $N-1$  order polynomial for  $N$  sampled data set. In (4), Lagrange interpolation method formulation is given [7].

$$y(x) = \sum_{j=1}^n y_j \prod_{k=1, k \neq j}^n \frac{x - x_k}{x_j - x_k} \quad (4)$$

The advantage of Lagrange method over Newton method is that the approximation centers the sample points, in another word, the points near the sample points have higher accuracy. So, it is decided to use Lagrange interpolation method.

c) *Rational interpolation*: This method generates a relation using algebraic fractions with polynomial numerators and denominators as in (5). This form can provide different shapes from Newton and Lagrange interpolation. The formulation is simple and works good in sample point intervals. But this form may cause asymptotic points because of having a denominator and should be aware of this.

$$y(x) = \frac{p_1 x^m + p_2 x^{m-1} + \dots + p_{m+1}}{q_1 x^n + q_2 x^{n-1} + \dots + q_{n+1}} \quad (5)$$

After the interpolation process, the quality of regression can be determined and be used in comparisons. A very common method for error determination is root-mean-square error (RMSE) method. The technique is simple and prone to comparison with other derives. If special conditions are not involved, the results without comparison are not meaningful data. Thus, a comparison is required with multiple sets for this study. The formulation of RMSE is given in (6).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (6)$$

### III. EXPERIMENT RESULTS

The required data for the calibration process are measured with nine sample points and for ten times for reliability. The averages were made from the data set. To clarify the input data, the current feedback voltage, a Kalman filter is used for extract the primary signals. Also, it is experienced that as the sampling rate is increased, the raw input data gets more regular. Using this method, the sampling process is carried out. In Table 1, the average values of the sample data are given for two equivalent electromagnets, with two current flow directions.

TABLE I. SAMPLE POINTS

Y- (Y <sub>n</sub> ) Electromagnet			Y+ (Y <sub>p</sub> ) Electromagnet		
Current (A)	Direction	Feedback (V)	Current (A)	Direction	Feedback (V)
0	forward	0,038	0	forward	0,014
0,5	forward	0,067	0,5	forward	0,045
1	forward	0,127	1	forward	0,105
1,5	forward	0,216	1,5	forward	0,198
2	forward	0,337	2	forward	0,323
2,5	forward	0,489	2,5	forward	0,480
3	forward	0,668	3	forward	0,675
3,5	forward	0,880	3,5	forward	0,918
4	forward	1,125	4	forward	1,185
0	backward	0,035	0	backward	0,015
0,5	backward	0,036	0,5	backward	0,018
1	backward	0,070	1	backward	0,055
1,5	backward	0,134	1,5	backward	0,125
2	backward	0,230	2	backward	0,231
2,5	backward	0,362	2,5	backward	0,373
3	backward	0,528	3	backward	0,550
3,5	backward	0,723	3,5	backward	0,769
4	backward	0,969	4	backward	1,030

In Figure 3, the graph forms of the samples are given.

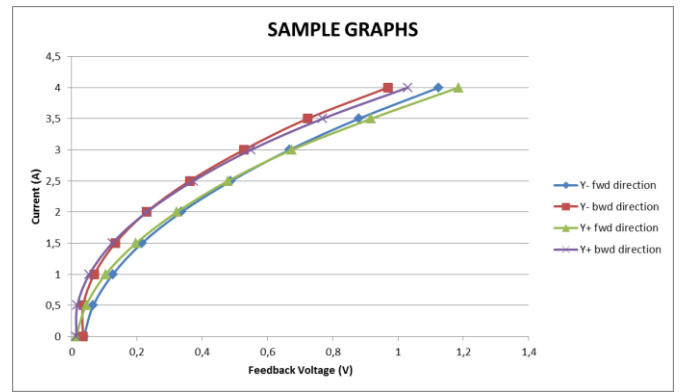


Fig. 3. Feedback voltage – current relationships of both electromagnets with current flows in both directions.

As the first step, Lagrange interpolation method is applied. All the sample points are used for the regression. Although more sampling points are expected to help building up more approximate result, as the order increases too much, the error with the intermediate data are getting larger and larger. In Figure 4, an example with 8<sup>th</sup> order is given.

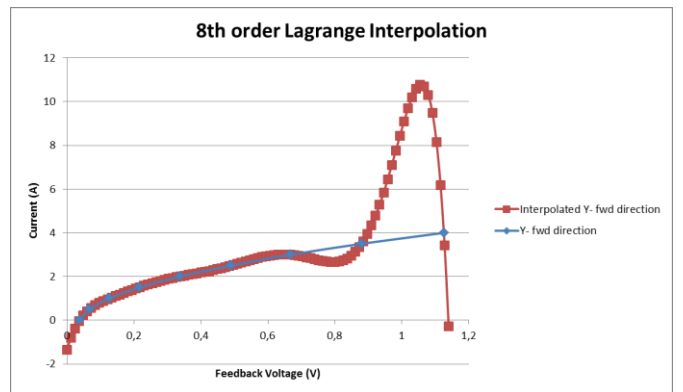


Fig. 4. Y<sub>n</sub> electromagnet with a forward direction current interpolation curve with 8<sup>th</sup> order feedback voltage – current relationship.

Generally, more than 2<sup>nd</sup> or 3<sup>rd</sup> order polynomial functions, the error for sampling points may be still satisfying, but for the rest of them it is not. So, to make it functional, the data set is divided into subdivisions and the whole range is handled in different intervals with different functions. After these processes, the polynomials in (7) and (8) are generated and Figure 5 is evaluated as an example result where the break point is picked as 1 A.

$$y_1(x) = -100,1x^2 + 27,75x - 0,91 \quad (7)$$

$$y_2(x) = 2,16x^3 - 5,67x^2 + 7,02x + 0,2 \quad (8)$$

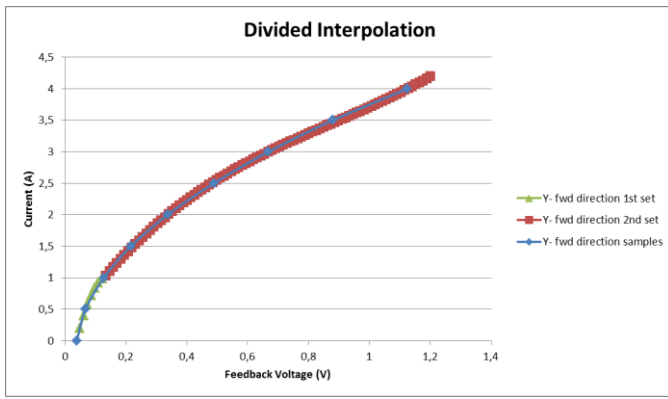


Fig. 5. Feedback voltage – current relationship after evaluation with divided interpolation for  $Y_n$  electromagnet with forward current flow.

Similarly, the same method fits to  $Y_p$  electromagnet with current in forward direction. Unfortunately, this method does not fit to the sample sets with currents in backward direction. In Figure 6 and 7, the graphs for backward direction are given.

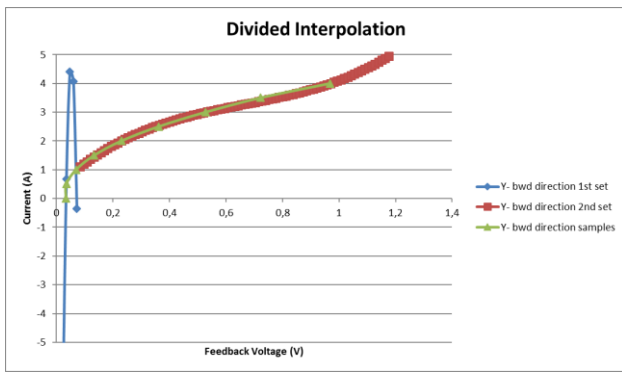


Fig. 6. Feedback voltage – current relationship after evaluation with divided interpolation for  $Y_n$  electromagnet with backward current flow.

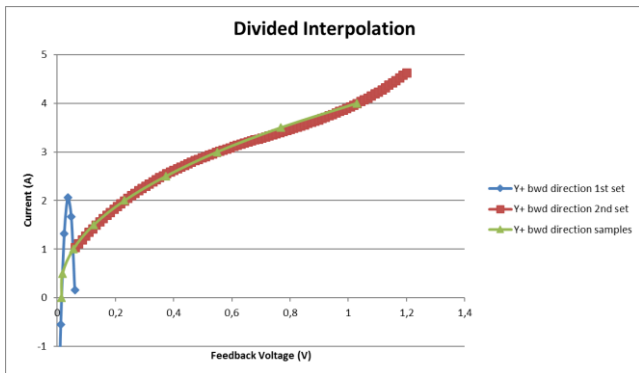


Fig. 7. Feedback voltage – current relationship after evaluation with divided interpolation for  $Y_p$  electromagnet with backward current flow.

To clarify these errors, a reduction in the number of sampling points for the first set is required, after that the curve can be refit with a lower order linear regression, with accuracy loss at nonignorable levels. So, partial interpolation is proposed for the next fitting. This step is handled using Matlab embedded functions. The result forms are given in Figure 8, 9, 10 and 11.

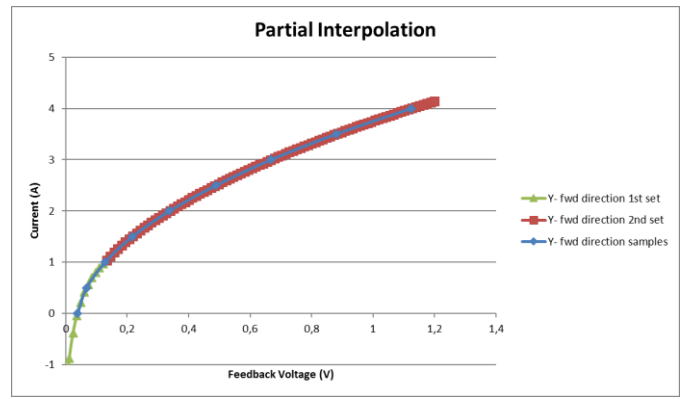


Fig. 8. Feedback voltage – current relationship after evaluation with partial rational interpolation for  $Y_p$  electromagnet with backward current flow.

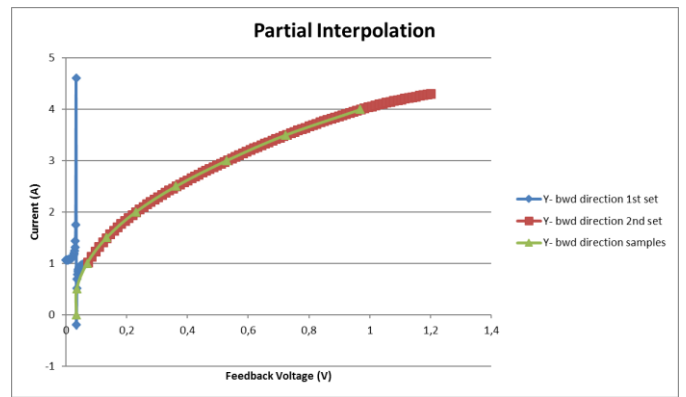


Fig. 9. Feedback voltage – current relationship after evaluation with partial rational interpolation for  $Y_p$  electromagnet with backward current flow.

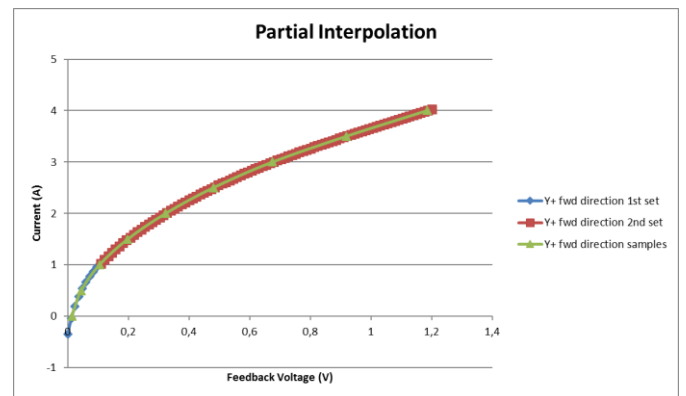


Fig. 10. Feedback voltage – current relationship after evaluation with partial rational interpolation for  $Y_p$  electromagnet with backward current flow.

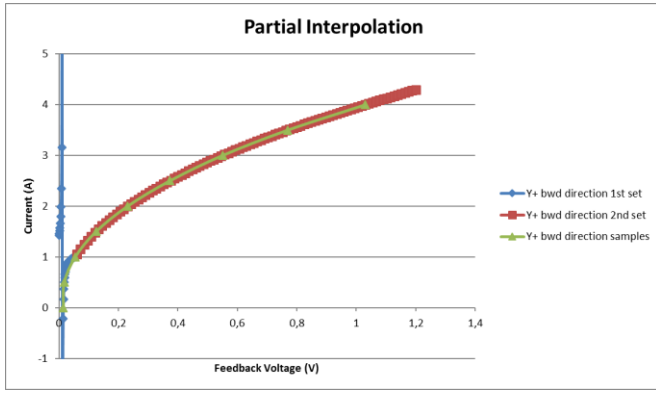


Fig. 11. Feedback voltage – current relationship after evaluation with partial rational interpolation for  $Y_p$  electromagnet with backward current flow.

#### IV. DISCUSSION

The partial interpolated graphs have higher accuracies than Lagrange interpolation and can be noticed by just looking at the figures when evaluating in full interval and considering intermediate points. When projected in a chart, the RMS error values for nine sampled points are given in Table 2 for Lagrange interpolation solution.

TABLE II. RMSE FOR EACH CALIBRATION WITH DIVIDED SETS USING LAGRANGE METHOD

	Y- forward	Y- backward	Y+ forward	Y- backward
RMSE	0,0194	0,0443	0,0149	0,0373
Normalized RMSE	0,0049	0,0111	0,0037	0,0093

For partial interpolation, the graph figure formulas are given in Table 3.

TABLE III. PARTIAL INTERPOLATION FORMULATIONS

	Formula	
	First Set	Second Set
Y- forward	$\frac{1,9355x - 0,0735}{x + 0,0453}$	$\frac{0,239x^4 - 1,2068x^3 + 3,5935x^2 + 1,371x - 0,0519}{x + 0,0508}$
Y- backward	$\frac{1,0303x - 0,0361}{x - 0,0339}$	$\frac{-0,9553x^4 + 1,3691x^3 + 1,389x^2 + 2,8048x - 0,0051}{x + 0,1368}$
Y+ forward	$\frac{2,069x - 0,029}{x + 0,0833}$	$\frac{0,9871x^4 - 3,1152x^3 + 5,1334x^2 + 0,6082x - 0,032}{x - 0,02}$
Y- backward	$\frac{1,0882x - 0,0163}{x - 0,0115}$	$\frac{0,5146x^4 - 1,8173x^3 + 3,7838x^2 + 1,6947x + 0,0119}{x + 0,0613}$

Using RMSE method, the results are given for partial interpolation in Table 4.

TABLE IV. RMSE FOR EACH CALIBRATION WITH DIVIDED SETS USING PARTIAL INTERPOLATION METHOD

	Y- forward	Y- backward	Y+ forward	Y- backward
RMSE	0,0194	0,0443	0,0149	0,0373
Normalized RMSE	0,0049	0,0111	0,0037	0,0093

RMSE	0,000086	0,2731	0,000061	0,2931
Normalized RMSE	0,000021	0,0683	0,000015	0,0733

#### V. CONCLUSION

In this paper, the calibration of electromagnet drivers is considered. The electromagnets are supposed to be used as Helmholtz coils and a couple of electromagnet drivers for each one are used in calibration process. The driver circuitry depends on H-bridge driving method and a shunt resistor is placed as feedback current sensor by measuring the voltage with OPAMP based amplifier. The current flow happens in both directions. Because of having nonlinearities with the feedback, a calibration process is needed.

The starting idea is to generate an iteration between each sampling points, which causes increment in parameters for each sampling points and point intervals. When thought about the system where the electromagnets are applied, because of the complexity of system's control algorithm, a general regression with the sampling points is desired for correlation. First trials are built onto Lagrange interpolation method because of its simple polynomial formulation expression. Some disadvantages are encountered with the form, so the set is divided into two subsets for easier evaluation and lessen the sampling points usage. As the result, the form is still not good enough and it is needed to decrease the numbers of sampling points, with a cost: error increment with regression. During this step, a critical limit is reached where the number of points should be decreased to aid the form with some critical faults as in Figure 6 and 7, especially with the calibrations where the current flows in backward direction.

Then, partial interpolation form is proposed as it provides a better form for intermediate points. Also, the results show that the partial interpolated graphs have higher accuracies from Lagrange interpolation and can be noticed by just comparing the figures. For better error comparison, RMSE results are determined. But these results show only the fitting qualities at sampling points.

For backward current calibrations, the asymptotes met in first sets can be deflected with coding during preprocessing step of sensor measurement.

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